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The influence of tensile stress on inductively coupled piezoceramic sensors embedded in fibre reinforced plastics

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Abstract

This paper demonstrates that embedded piezoelectric sensors can survive loads much higher than predicted by their material properties. It shows the potential for piezoceramic sensors to estimate structural loads when embedded in composites. To show this, embedded sensors were subjected to stresses and strains which were significantly greater than the recommended operating limits of their piezoceramic constituents. A novel data acquisition method enabled ultrasonic guided wave measurements to be recorded wirelessly from the embedded transducers, key to minimising the impact of embedded transducers. The data recorded by the piezoceramic transducers exhibited a reversible load dependence, with the measurements returning to the stress free values upon removal of the applied load. The guided wave measurements recorded by transducers embedded in glass fibre reinforced composites showed no degradation after being subjected to tensile strains of 1.07%. When embedded in a carbon fibre reinforced plastic sample which was loaded to failure, the transducers remained operational, however, sensor performance was shown to be degraded after being subjected to tensile stresses as high as 606 MPa. This offers the potential to build sensors to characterise overload in a component.

Introduction

Embedding sensors in composite parts has several potential benefits. It can offer protection, improving sensor robustness, minimise their impact on the geometry of a structure and ensure that any sensors experience the same conditions as the part, therefore offering new measurement possibilities. For sensors embedded in composite parts to be of practical use though they must survive all extremes of possible structural loads, while providing consistent measurements. This paper investigates the behaviour of piezoceramic sensors embedded in composites when under applied stress, and evaluates the consistency of the measurements recorded by the sensors after being subjected to load cycles. In doing this we aim to increase the range of applications of embedded piezo sensors for composites.

Experimental work in the literature shows that the electromechanical properties of piezoceramics exhibit a stress dependence [1, 2], and that the performance can be degraded through depolarisation when operated at high stress [3, 4, 5]. This behaviour depends on the composition of the piezoceramic, with different piezoceramic configurations exhibiting different sensitivities and abilities to resist mechanical stress [3]. Several researchers have investigated how permanently installed sensors can be used to characterise themselves and the structure [6, 7] through using these changes, but this is a relatively unexplored area. Piezoceramic sensors embedded in composite parts will be subject to complex loading conditions, with stresses and strains acting in multiple directions. The complexity of the load transfer between the sensor and surrounding composite is then further increased by the number of different materials present, which creates complex stress and strain gradients. These together make it unclear if embedded piezoceramic sensors can survive the environment.

A number of experimental works have been carried out to improve the understanding of how embedding items [8, 9, 10], and more specifically piezoceramic transducers [11, 12, 13], inside composites affects the strength of the composite host. The results suggest that providing the embedded item is relatively thin, and embedded away from the critical interfaces of the laminate (eg away from primary loaded plies), the effect on strength is minimal. These studies assessed the effect of embedment on the structural integrity of the composite, and focus on identifying strategies to mitigate its reduction. When embedding piezoceramic components inside structural composites, the stress dependence and potential to degrade performance through depolarisation at high stress mean that the integrity of the sensor must be evaluated as well. Mall et al. showed that the

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voltage output of embedded piezoceramics decreased after being subjected to monotonic and fatigue loads in excess of the recommended operating limit of the transducers [11, 14]. It was shown that depolarisation was responsible for the decrease in voltage output, by recovery of the output voltage once the embedded transducers were repled with a large direct current (DC) voltage [15]. Lin et al. demonstrated that ultrasonic measurements made by embedded transducers remained consistent when subjected to strains below their design limit [16]. The results of the discussed experimental works suggest that to avoid degradation in performance of an embedded piezoceramic component, the strain applied to the composite must not exceed the operating limit recommended by the manufacturer of the piezoceramic. Whilst these works go some way to defining the working limit of composite parts containing embedded piezoceramic parts, none of the results characterise the performance of embedded transducers when under applied stress which is an important consideration for online health monitoring. Some work has been carried out on piezoceramic sensors embedded in concrete under load [17, 18] but this has not explored the full range of possible loads.

In this study piezoceramic transducers were embedded inside fibre reinforced composites and subjected to tensile stress. The specific piezoceramic material studied in this work was NCE51 from Noliac. NCE51 is a modified lead zirconate titanate (PZT) composition categorized as a soft piezoceramic with high coupling coefficients and low resistance to stress depolarisation [19]. The data acquisition system used to record measurements from the embedded PZT transducers uses a novel inductively coupled approach. Inductive coupling between an external probe, and coils connected to the embedded PZT transducers allowed measurements to be recorded wirelessly. The embedded transducers generated ultrasonic guided waves, which were used to record A-scan measurements. For a more detailed description of the acquisition system, and principle of operation when embedded in composites please refer to a number of papers by Zhong and the authors of this publication [20, 21, 22, 23]. The influence of tensile stress on performance of the embedded transducers was monitored by extracting the amplitude and centre frequency of the recorded A-scan data. Transducers were embedded into glass fibre reinforced plastic (GFRP) specimens and subjected to tensile strains which were significantly greater than the 0.2% operating limit recommended by the piezoelectric manufacturer. Transducers were then embedded into carbon fibre reinforced plastic (CFRP) and subjected to high stress. In both cases the embedded transducers displayed a reversible stress dependence, with the amplitude of the guided wave measurements decreasing with increasing tensile stress, and then returning upon removal of the applied stress. This behaviour demonstrates that embedded PZT transducers generating guided waves have the potential for estimating structural loads. The survivability of the PZT transducers was evaluated by comparing the measurements recorded before and after the load cycles were applied. In all cases the transducers survived and remained operational, even under global stresses far in excess of the manufacturers design limits.

Table 1. Details of the sensors embedded inside the GFRP specimens.

Electrical connection	Encapsulating layer	Laminate thickness (mm)
Inductively coupled	None	0.3
Inductively coupled	LF Bond ply	0.45
Wired	None	0.3

Manufacture and Methods

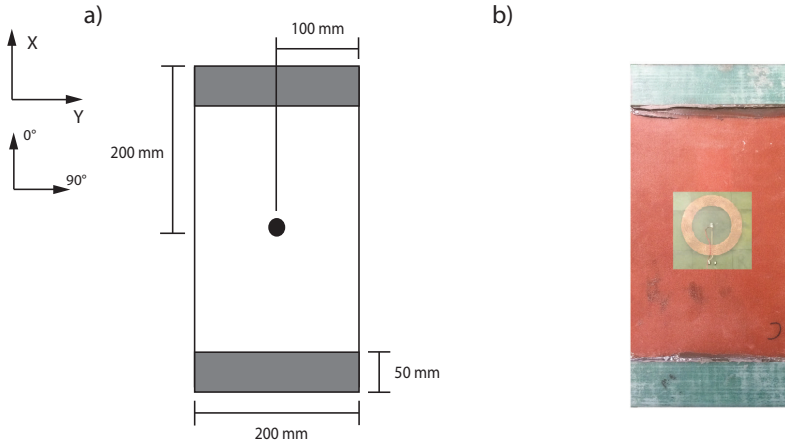
This section contains details of the manufacturing process used to produce composite panels containing embedded piezoceramic transducers, and the testing methodology used to evaluate the effect of tensile stress on the guided wave measurements recorded by the embedded transducers.

Specimen Manufacture

GFRP plates were manufactured from a unidirectional fibre reinforced prepreg material (Hexcel, E-Glass 913 prepreg). The laminates were assembled using the hand layup process. Each laminate was manufactured from a total of 20 plies, giving an average plate thickness of 3.09 mm. The dimensions and layup of the GFRP plates is shown in Figure 1a. A single transducer manufactured from NCE51 was embedded at the mid-plane of each stacking sequence, at the centre of the plates (Figure 1a). The embedded transducers measured 16 mm in diameter and 0.3 mm thickness. The 200 mm width and 400 mm length of the plates enabled guided wave signals reflected from the edges to be separately resolved in the pulse echo A-scan data recorded by the embedded transducers. The assembled stacking sequences were cured inside an autoclave at 125 °C under 700 KPa of pressure for 1 hour, in line with the manufacturers recommendations.

A total of three specimens were manufactured (Table 1). Two of the specimens contained inductively coupled sensors. In the third a wired sensor was installed to investigate and control for the effect of the inductive coupling. All of the specimens were used to evaluate the ability of embedded PZT to survive high strains, and monitor the stress dependence of embedded PZT. One of the embedded sensors was encapsulated within a compliant polyimide layer coated with a b-staged acrylic adhesive (Dupont, LF Bond ply) as this has been shown ([22]) to offer the best structural performance. Comparison with the responses of sensors without an encapsulating layer allowed the influence of the encapsulating layer on load resistance to be assessed. It was thought that the compliant encapsulating layer would deform through shear and reduce the load transferred to the embedded transducer.

To investigate the ability of embedded piezoceramic to resist high stresses a single CFRP specimen was manufactured from a unidirectional carbon fibre reinforced prepreg material (Hexcel, AS4/8552). The laminate was assembled using the hand layup process from a total of 18 plies, giving a total cured thickness of 2.33 mm. Two inductively coupled sensors were embedded at the mid-plane of the stacking sequence. The in-plane location of the sensors is shown in Figure 2a. Both of the embedded sensors were encapsulated within a single layer of LF Bond ply, with this layer providing



Layup: $[0^\circ, 90^\circ, 0^\circ, 90^\circ, 0^\circ, 90^\circ, 0^\circ, 90^\circ]_S$

Figure 1. Dimensioned diagram of the GFRP specimens. The black circle at the centre of the plate shows the location of the embedded transducers. b) GFRP specimen with the inductance probe mounted above the embedded sensor.

Table 2. Details of the sensors embedded inside the CFRP pitch catch specimen.

Electrical connection	Encapsulating layer	Sensor thickness (mm)	Laminate thickness (mm)
Inductive	LF Bond ply	0.45	2.33

electrical insulation from the conductive carbon fibres. The sensors were used in a pitch catch configuration (A-scan measurements were made between the two sensors), which removed the influence of the specimens edges on the first arrival and allowed the specimen width to be reduced without affecting the results. A narrow specimen was required due to limitations in the available tensile testers, and the high strength of the CFRP material. The assembled stacking sequence was cured inside an autoclave at 180 °C under 700 KPa of pressure for 120 minutes in line with the manufacturers recommendations.

Experimental Method

Tensile testing was carried out using an Instron 1342 test machine (Instron, United Kingdom), equipped with a calibrated load cell of 250 kN. Each specimen was gripped at the end tabs with a clamping pressure of 18.5 MPa by a set of grips 100 mm wide. The clamping pressure prevented slip occurring during testing. All of the testing was carried out under load control. A loading rate of 2 kN/s was used to increase the tensile force applied to each specimen. In cases where a loading rate of 2 kN/s resulted in a ramp

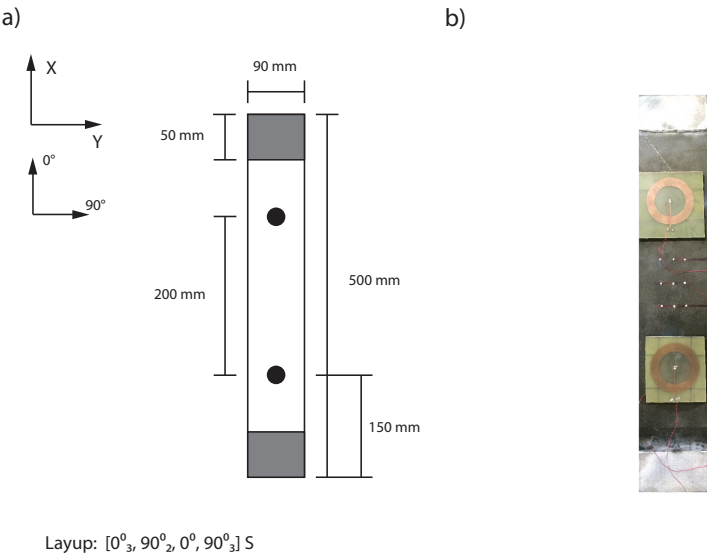


Figure 2. Dimensioned diagram of the CFRP specimen. The two black circles show the location of the embedded transducers. b) CFRP specimen with two inductance probes mounted above the inductively coupled sensors.

Table 3. Tensile stress and strain applied to the GFRP specimens. A load cycle similar to that illustrated in Figure 3 was used to record guided wave data at each stress level.

ϵ_x (%)	0.1	0.18	0.28	0.37	0.48	0.59	0.69	0.80	0.91	1.07
σ_x (MPa)	25	46	72	95	123	152	177	205	232	277

time of less than 20 seconds, an absolute ramp of 20 seconds was selected to prevent overshoot in the tensile force applied to the specimens. Load control was selected rather than displacement control to prevent the specimens being put into compression once unloaded.

Figure 3 illustrates the load cycle used to record guided wave measurements under tensile stress. The stress was increased to the desired level, and then held for 60 seconds. Guided wave A-scan data was then recorded by the embedded PZT transducers whilst a constant tensile stress was applied to the laminates. The specimens were then unloaded at a rate of 2 kN/s, until the applied force was 2 kN. This process was repeated to record guided wave A-scan data under increasing levels of tensile stress. To identify potential degradation in sensor performance guided wave measurements were recorded before and after testing. A video extensometer system (Imetrum, United Kingdom) was used to measure the strain applied to each specimen.

The grips used to apply the tensile force to the GFRP specimens were 100 mm wide, this was half the 200 mm width of the GFRP specimens (shown in Figure 1a). As a

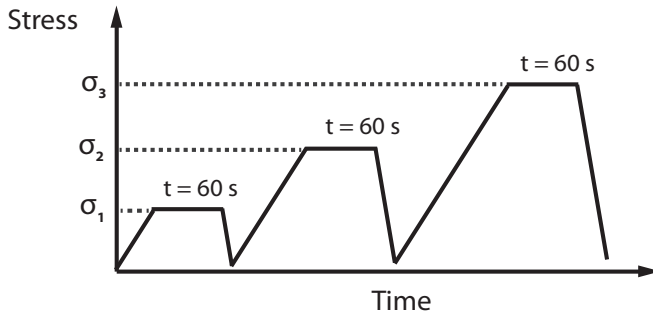


Figure 3. Illustrative example of the load cycle used to record guided wave measurements under a constant stress. In this case three loading increments were applied, at increasing levels of tensile stress. Guided wave A-scan measurements were recorded during the 60 second dwell, under a constant tensile stress. A similar load cycle was used to record guided wave A-Scan data at each of the tensile stress increments shown in Tables 3 and 4.

Table 4. Tensile stress and strain applied to the CFRP specimen. A load cycle similar to that illustrated in Figure 3 was used to record guided wave data at each stress level.

ϵ_x (%)	0.050	0.10	0.147	0.205	0.254	0.305	0.356	0.413	0.464	0.494
σ_x (MPa)	34	68	102	136	169	203	237	271	303	338

consequence of the grips being narrower than the specimens, stress concentrations were generated in the GFRP plates. To ensure that the specimens survived the load cycle, the maximum stress applied to the specimens was a tensile stress of 277 MPa (at the sensor location). Table 3 shows the loading increments applied to the GFRP specimens. Guided wave A-scan measurements were recorded at each of the loading increments using a similar loading approach to that shown in Figure 3. The strain was measured across the region of the plate in which the PZT sensors were embedded using a videogauge system (Imetrum, United Kingdom). Measurement of the strain in the region of the plate containing the sensors, and the material properties available in the materials data sheet (Hexcel EG-913) allowed the tensile stress to be estimated using Hooke's law.

The 90 mm width of the CFRP specimen allowed the specimen to be gripped across the entire width, and therefore loaded uniformly with no stress concentration at the edge of the grips. The strain was measured across the centre of the specimen using a videogauge system (Imetrum, United Kingdom), and the tensile stress calculated by dividing the applied force by the cross sectional area of the specimen. Guided wave A-scan measurements were recorded in a pitch-catch configuration between the two sensors. A similar load cycle to that shown in Figure 3 was used to record A-scan data under each of the loading increments shown in Table 4.

The system used to acquire ultrasonic guided wave data from the embedded sensors consisted of a laptop (Lenovo G500), a combined signal generator and oscilloscope (HS3 Handyscope), and a set of transmit and receive coils for inductive coupling to the

Table 5. Material strength and operating limits of NCE51. The operating limits refer to the loads above which the material begins to depolarise. The failure strain (ϵ^*) was estimated as that of another soft piezoceramic characterised in the work of Fett et al. [24]. All other data was provided by the manufacturer.

Advised operating limits			Material strengths		
ϵ	σ_t	σ_c	ϵ^*	σ_t^*	σ_c^*
0.2%	No available data	50 MPa	1.5% [24]	80 MPa	600 MPa

Table 6. Additional loading increments applied to the CFRP specimen. After each loading increment the specimen was removed from the test rig and guided wave A-scan data recorded.

ϵ_x	(%)	0.494	0.590	0.702	0.813	0.926
σ_x	(MPa)	338	404	472	539	606

sensor(for more detail see [20]) fixed to the surface of each specimen. An effective input signal of a 4 cycle hanning windowed toneburst with a centre frequency of 165 kHz was transmitted to the embedded sensors, which resulted in the generation of ultrasonic guided waves. The 165 kHz centre frequency of the input signal meant that the sensors operated at relatively low frequency-thickness products of 0.51 MHz.mm for the GFRP specimens, and 0.38 MHz.mm for the CFRP specimen. The relatively low frequency-thickness products ensured that the guided waves generated by the sensors were in the largely non-dispersive region of the fundamental symmetric wave mode (S_o), below the cut-off frequency of the higher order modes.

The electromagnetic coupling between the probe and the inductively coupled sensors is strongly dependent on the relative distance between the coils in the probe, and the embedded coil [21]. A pin of diameter 10 mm and height 5 mm was used to mount an inductance probe to the front face of the specimens containing inductively coupled sensors. The inductance probe was mounted at the centre of each sensor, which ensured that the probe translated with the sensor as the plate deformed. Fixing the probes to the specimen minimised the potential movement between the coils, and allowed the influence of tensile load to be investigated separately from misalignment effects.

All of the specimens were subjected to tensile stresses that exceeded the material strength of the embedded transducers. Table 5 details the material strength and recommended operating limits of NCE51. To identify potential degradation in sensor performance guided wave A-scan measurements were recorded before and after the load increments shown in Tables 3 and 4 were applied to the specimens. To investigate the influence of high stress on embedded PZT a further series of load increments (shown in Table 6) were applied to the CFRP specimen. After each incremental increase in tensile stress the specimen was removed from the Instron test rig, and guided wave A-scan data recorded with the specimen in a stress free condition.

Stress dependence of measurements recorded by embedded piezoceramic sensors

This section characterises the influence of tensile stress on the A-scan guided wave measurements recorded by embedded piezoceramic transducers.

Stress dependence of measurements from transducers embedded in GFRP

Figure 4a, shows pulse echo data recorded by an inductively coupled transducer embedded in GFRP, the laminate is in a stress free condition. The first arrival located at approximately 0.06 ms corresponds to the summation of the S_o waveforms reflected from the two edges 100 mm from the transducer (Figure 1a). The subsequent waveforms are associated with reverberations. The large signal before the first arrival is referred to as crosstalk, and is associated with cross communication between the input and output channels of the data acquisition system. The amplitude, and centre frequency of the first arrival were measured while under load at increasing stress levels (Table 3).

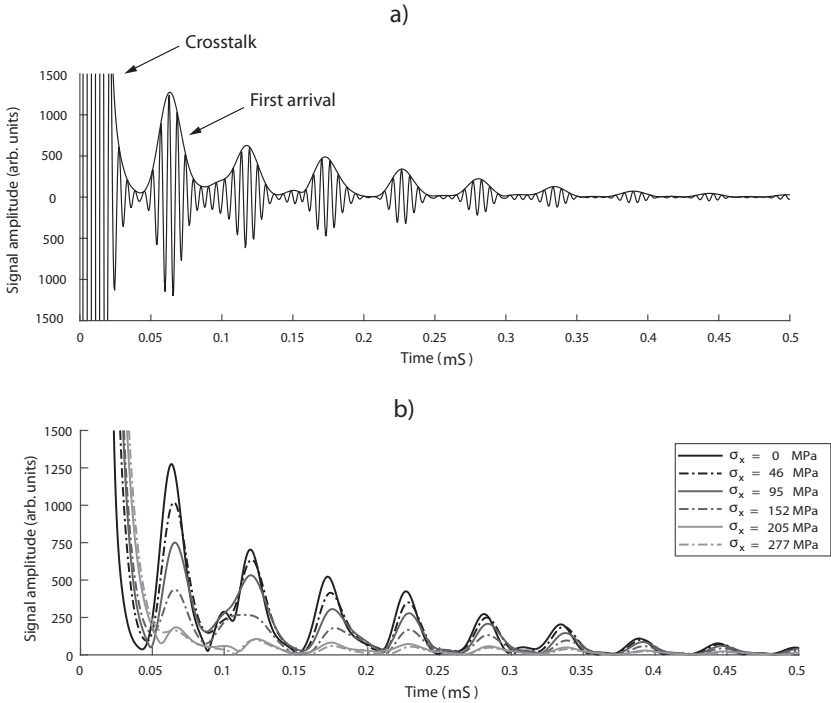


Figure 4. a) Guided wave A-scan data recorded by the inductively coupled transducer embedded inside GFRP, with the specimen in a stress free condition. The transducer was not encapsulated in LF Bondply. b) Hilbert transforms of the A-scan data recorded under increasing levels of tensile stress.

Figure 4b, shows the Hilbert transforms of the A-scan data recorded by the inductively coupled transducer (no encapsulating layer) with increasing tensile stress. As the stress was increased the amplitude of the recorded signals reduced. Figure 5a, plots the amplitude of the first arrival with increasing stress. The values were normalised by the amplitude recorded before testing. All of the embedded transducers show the same behaviour; a decrease in amplitude with increasing tensile stress. The agreement between the inductively coupled and wired systems, suggests that the mounting of the inductance probe prevented relative movement between the probe and the embedded coils, and that any changes in geometry of the embedded coils due to deformation of the specimen had a negligible effect on the amplitude of the recorded data. If either of these effects were significant it would have resulted in disparity between the amplitude measurements recorded by the wired and inductively coupled transducers.

Backlight illumination was used to inspect visually for any failures in the part and did not show any delaminations forming around the sensors. However, transverse cracks which ran across the full width of the samples were visible. The cracks were spread uniformly over the specimens, indicating that the sensors were not responsible for their generation. Upon removal of the applied stress the amplitude of the ultrasonic measurements returned to their original values (covered in more detail in Section). The recovery of amplitude shows that damage formation in the composite was not responsible for the amplitude reduction.

The reduction of signal amplitude with applied stress is thought to be associated with the stress dependence of the piezoelectric coefficients of the embedded piezoceramic [2, 3]. This is supported by the work of Zhang et al., who found that the piezoelectric coefficients of soft piezoceramics decreased when under applied stress, and that the coefficients either partially or fully recovered depending on the magnitude of the applied stress [3], which is in agreement with these measurements. This reversible stress dependence provides embedded piezoceramic transducers with the potential to be used as tools for estimating structural load.

In addition to affecting the amplitude of the ultrasonic first arrivals recorded by the embedded transducers, the applied stress altered their centre frequency. Figure 5b, shows the frequency shift on the signals recorded by the sensors embedded in GFRP. It is thought that variations in capacitance of the transducers due to stress induced changes in the permittivity of the transducers were responsible for the observed frequency shifts [2, 3]. The measurements recorded by the inductively coupled sensors were subjected to much larger frequency shifts than those made with the wired transducer. The different dynamics of the wired and inductively coupled systems were responsible for the contrasting responses to stress. The inductive coupling is operated close to resonance (to ensure a reasonable response), where small shifts in the capacitance of the transducer can have a large impact on the centre frequency of the recorded signals [20, 21]. The ultrasonic measurements recorded using the wired transducer did not exhibit the same electrical resonance, and were therefore subjected to much smaller frequency shifts. Upon removal of the applied load the centre frequencies returned to their original values.

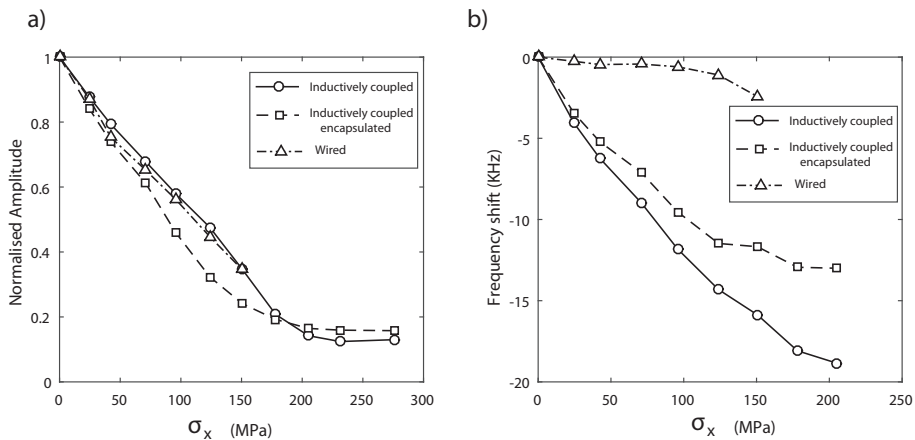


Figure 5. a) Amplitude of the first arrival plotted against the applied tensile stress. The amplitude has been normalised by that recorded with the laminates in a stress free condition. b) Frequency shift against the tensile stress.

The stress dependence of measurements recorded by transducers embedded in CFRP

The increased stiffness of the carbon fibres in the CFRP laminate (compared to GFRP) was expected to alter the load transfer, and produce a different response to that observed in the GFRP specimens. To characterise the effect of increased fibre modulus, ultrasonic measurements were recorded between two transducers embedded in CFRP at increasing tensile stress (Table 4). Figure 6a, shows an example of the ultrasonic data recorded by the sensors with the specimen in a stress free condition. The waveform located at 0.05 ms corresponds to the direct arrival of the S_0 mode between the sensors. Table 4 shows the loading increments applied to the CFRP specimen. The initial crosstalk in the pitch catch CFRP data (Figure 6) was much smaller than that observed in the pulse echo GFRP data (Figure 4). The reason for this was the 200 mm separation of the transmit and receive coils in the pitch catch configuration (shown in Figure 2a), reducing the electrical crosstalk, resulting from mutual inductance, between the input and output channels.

The Hilbert transforms of the guided wave A-scan measurements recorded under tensile stress are shown in Figure 6b. The figure shows that the amplitude of the recorded signals decreased as the tensile stress applied to the CFRP specimen increased.

Figure 7a, shows the amplitude of the direct arrival with increasing stress. The values were normalised by the amplitude recorded before testing. The application of tensile stress to the CFRP specimen, resulted in a small increase in amplitude at low stresses (when below 100 MPa, Figure 7a). This increase was followed by a decrease in amplitude, as the applied stress was increased. Similarly to the GFRP specimens, the general trend was a decrease in amplitude at increasing tensile stress. The decrease is

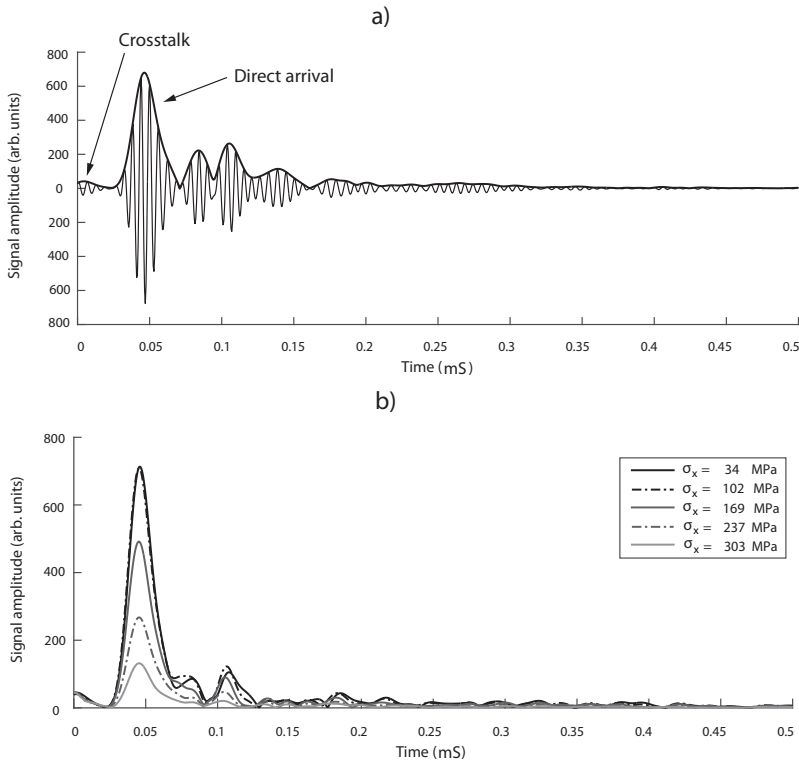


Figure 6. a) Pitch catch ultrasonic data recorded by the sensors embedded inside the CFRP specimen, with the specimen in an unloaded state. b) Hilbert transforms of the data recorded in the CFRP specimen at increasing tensile stress.

thought to be associated with the stress dependence of the piezoelectric coefficients of the transducers [3]. However, the slight increase in amplitude at low stress was not observed in the GFRP specimens. The presence of overlapping signals in the pulse echo data (multiple edge reflections, and large initial crosstalk) may have obscured the detection of this effect in the GFRP specimens.

The rate of amplitude reduction with stress and strain differed in the GFRP and CFRP specimens (Figures 5a and 7a). In the GFRP specimens, the amplitude was reduced to 20% of its stress free value by a stress of 200 MPa and strain of 0.8%, whereas, the amplitude reduced to 20% of its stress free value under a stress of 300 MPa and strain of 0.45% in the CFRP sample. The difference in responses suggests that variations in material properties result in different load transfer efficiencies, meaning that the ratio of stress and strain applied to the composite and that transmitted to the embedded transducer differ for different materials. The dependence of load transfer efficiency on material properties renders universal criteria for the acceptable stress or strain which can be

applied to a composite part containing sensors unsuitable, as the load transfer mechanism will vary between different material systems and layup configurations. Ultimately when embedding sensors in real systems it will be a key requirement to understand this variability.

Figure 7b, shows the frequency shift applied to the signals with increasing tensile stress. The centre frequency of the signals reduced, as the tensile stress increased. The reduction in frequency was similar to the behaviour of the inductively coupled sensors embedded in GFRP. The rate of this reduction in centre frequency with applied stress was different to that observed in the GFRP specimens. The potential reasons for this difference are the same as those outlined in the previous section.

These results have shown that the amplitude and frequency of guided wave measurements recorded by embedded piezoceramic transducers are dependent on the stress applied to the composite, and that by exploiting this phenomenon, embedded piezoceramics could be used to estimate structural loads. The following section will explore the ability of embedded piezoceramics to survive and maintain consistent performance after being subjected to high loads outside of their nominal operating regime and cyclic loading of increasing amplitude.

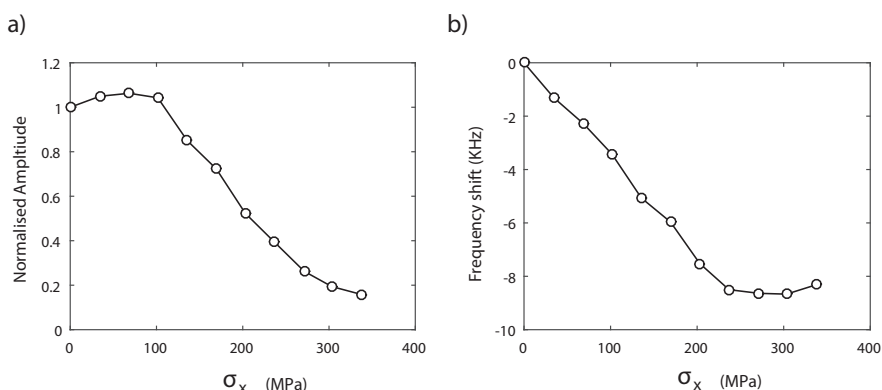


Figure 7. a) Amplitude of the direct arrival, plotted against tensile stress applied to the CFRP specimen. The amplitude has been normalised by that recorded with the specimen in a stress free condition. b) Frequency shift applied to the A-scan data plotted against stress.

Table 7. Variation in the amplitude and centre frequency of the A-scan data recorded by the inductively coupled transducers embedded in GFRP: With the specimens left in ambient laboratory conditions for 24 hours, and after being subjected to a load cycle containing a maximum tensile stress of 277 MPa, and maximum tensile strain of 1.07%.

	Specimen	Amplitude change	Frequency shift
Ambient conditions	No coating	$\pm 2.7\%$	± 0.27 kHz
	Encapsulated	$\pm 2.2\%$	± 0.43 kHz
After tensile testing	No coating	$\pm 2.1\%$	± 0.25 kHz
	Encapsulated	$\pm 2.4\%$	± 0.50 kHz

The survivability of piezoceramic sensors embedded in fibre reinforced composites

Consistency of measurements recorded by piezoceramic embedded in GFRP

Guided wave A-scan measurements were recorded before and after the two GFRP specimens containing inductively coupled sensors were loaded in tension. The recorded data was used to evaluate whether there was any degradation in the performance of the embedded transducers. The load cycle applied to the specimens contained each of the loading increments shown in Table 3, which corresponded to a maximum tensile stress of 277 MPa and tensile strain of 1.07%.

Table 7, characterises ultrasonic data recorded by the embedded sensors before and after load testing, and compares it to the variation seen in the laboratory over a 24 hour period, in order to understand the environmental noise inherent in the measurements. Table 7 indicates that there was no measurable loss in performance of the embedded transducers, with the variation in the parameters extracted from the guided wave A-scan data within that observed when the specimens were left in ambient laboratory conditions for 24 hours.

Despite the GFRP specimens being subjected to stresses and strains much larger than the recommended 0.2% strain limit, and 80 MPa tensile strength of NCE51 there was no measurable loss in performance. The results show that the load transfer between the transducer and composite is inefficient, which allows the embedded piezoceramic to survive and maintain consistent performance after being subjected to loads well in excess of its recommended operating limits, and material strength (Refer to Table 5). Potential improvements in the ability of transducers to resist structural loads due to the presence of the compliant encapsulating layer could not be investigated, as in no case was there a measurable loss in performance of the embedded transducer.

Consistency of measurements recorded by piezoceramic embedded in CFRP

The ability of embedded transducers to resist high stress was investigated by analysing the A-scan measurements recorded by transducers embedded in CFRP, before and after

Table 8. Variation in the amplitude and centre frequency of the A-scan data recorded by the sensors embedded in CFRP over a 24 hour period in ambient laboratory conditions.

	Amplitude change	Frequency shift
Ambient conditions	$\pm 2.5\%$	± 0.32 KHz

the CFRP specimen was subjected to a tensile load cycle. This was carried out in the CFRP specimen due to its higher strength allowing a greater range of loads to be investigated.

After each of the load increments shown in Table 4 were applied to the CFRP specimen, the laminate was removed from the test machine and guided wave A-scan data recorded. A further four loading increments were applied to the specimen (shown in Table 6). After each loading increment the specimen was removed from the test machine, and guided wave A-scan data recorded with the specimen in a stress free state. The largest loading increment after which data could be recorded was a tensile stress of 606 MPa, and strain of 0.926%. The CFRP specimen failed at the grips at a tensile stress of 651 MPa, preventing further measurements.

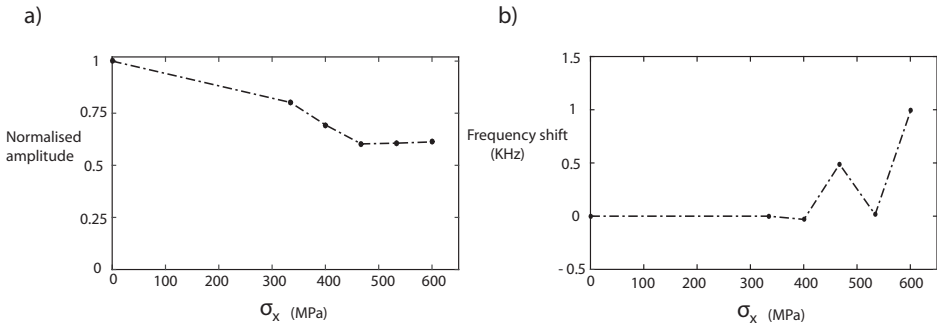


Figure 8. Signals recorded in an unloaded state after being subjected to the stresses marked on the x-axis, a) Amplitude of the direct arrival in the CFRP specimen. b) Frequency shift of the direct arrival in the CFRP specimen. In both cases the data has been normalised to the amplitude recorded before testing.

Figure 8a, shows the amplitude of the direct arrival recorded in the stress free condition after the CFRP specimen was subjected to increasing tensile stress. That is the specimen was loaded, and its ability to recover from that load subsequently recorded. A tensile stress of 467 MPa reduced the amplitude to 60% of that recorded before testing. There were no further reductions as the specimen was loaded up to 601 MPa. The measured amplitude changes were much greater than the range of amplitudes observed in the ambient lab data (shown in Table 8), which indicated that the amplitude reduction was associated with the tensile load rather than any environmental affects. The reduction is not expected to be associated with any damage in the composite; as the presence of matrix

cracks had no effect on the guided wave measurements made in the GFRP specimens, and the linear stress strain response of the CFRP specimen did not indicate the presence of any delaminations. The degradation in performance of the sensor is thought to be associated with depolarisation of the piezoceramic, as was observed in the experimental work of Mall [15].

The frequency shift applied to the ultrasonic data is plotted in Figure 8b. Small shifts in the centre frequency of the measurements were observed (less than 1% of the 165 KHz centre frequency). The data shows no clear trend, however, the changes were greater than the frequency shifts recorded over a 24 hour period in the lab (Table 8), suggesting that the applied load may permanently alter the frequency of the recorded data, and hence PZT. A possible cause for this could be stress induced variations in the permittivity of the piezoceramic [3].

The piezoceramic transducers embedded in CFRP were able to record guided wave measurements after being loaded up to a tensile stress of 606 MPa, which is far greater than the 80 MPa tensile strength of NCE51. Depolarisation was believed to be responsible for the reductions in amplitude after the CFRP was subjected to high stress [3, 4, 5]. This is potentially a highly useful feature as the sensor is effectively able to record very high stresses that it has seen through this depolarisation, essentially acting as overload measurements.

Conclusion

This paper has shown that embedded piezoceramic transducers have the potential to estimate structural loads in composite parts. The guided wave measurements recorded by the embedded transducers were heavily influenced by the tensile stress applied to the composite part. Both the amplitude and frequency of the guided wave data exhibited a reversible stress dependence. The source of this stress dependence is thought to be variations in the electromechanical properties of the piezoceramic [2, 3]. Exploiting this phenomenon could enable embedded piezoceramic sensors to estimate the structural loads applied to operational composite structures. As a consequence of this behaviour, researchers investigating the survivability of embedded piezoceramics should ensure that measurements are recorded in a stress free condition to prevent the stress dependence influencing their results.

The embedded transducers were shown to be capable of surviving static loads that were significantly greater than their advised operating limits, and material strength. Embedded piezoceramic transducers maintained consistent performance after tensile strains of 1.07% and stresses of 277 MPa were applied to GFRP specimens. The applied loads were considerably larger than the recommended strain limit of 0.2%, and 80 MPa tensile strength of the piezoceramic (NCE51, Noliac). The ability of embedded piezoceramic to survive loads well in excess of their recommended operating limits and material strength is thought to be associated with the mismatch in material properties of the composite, piezoceramic, and compliant materials surrounding the transducer reducing the efficiency of the load transfer. The results suggests that operating limits based upon

the assumption that all of the structural strain is transmitted from the composite to the embedded transducer are highly conservative.

Transducers embedded in CFRP were able to record ultrasonic measurements after being subjected to tensile stresses of 606 MPa, however, amplitude reductions were observed in the ultrasonic data. The observed amplitude reduction in a stress free condition was believed to be associated with stress depolarisation of the piezoceramic, as was observed in the work of Mall et al. [3]. The transducers used in this study were manufactured from NCE51, which is categorized as a soft piezoceramic, and is therefore susceptible to stress depolarisation. The use of inductive coupling increases the sensitivity to this effect due to the resonant operating regime. In practical applications, this is likely to be beneficial where an overload sensor could be very useful. If the measurement of overload is not helpful and embedded transducers could be subjected to high stresses, piezoelectric materials with increased resistance to stress depolarisation should be used.

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